In comparing these observations with those made during the 1878 eclipse, it must be remembered that the conditions of observation on the two occasions were widely different. The observations in the West Indies were made at the sea's level, in a perfectly humid atmosphere and with the sun at no greater altitude than 19°. Professor Langley, in 1878, observed from the summit of Pike's Peak in the Rocky Mountains at an altitude of 14,000 feet, in a relatively dry atmosphere and with the sun at an altitude of 39°.

From observations on the transmission of sunlight through the earth's atmosphere (Abney, 'Phil. Trans.,' A, vol. 178 (1887), p. 251) one of the authors has developed the law of the extinction of light, and, by applying the necessary factors, it is found that the intensity of the light during the 1886 eclipse, as observed at Grenada, is almost exactly half of that of which would have been transmitted from a corona of the same intrinsic brightness when observed at Pike's Peak. Hence to make the observations of Professor Langley comparable with those of the authors, the numbers denoting the photometric intensity of the corona in 1878 must be halved. The result appears, therefore, that whereas in 1878 the brightness of the corona was 0·0305 of a standard candle at a distance of 1 foot, in 1886 it was only 0·0124 of a candle at the same distance. Several of the observers of the West Indian Eclipse (including one of the authors) were also present at the eclipse of 1878, and they concur in the opinion that the darkness during the 1886 eclipse was very much greater than in that of 1878. The graduations on instruments, chronometer faces, &c., which were easily read in 1878, were barely visible in 1886. In explanation of this difference in luminous intensity it must not be forgotten that the 1878 eclipse was not very far removed from a period of maximum disturbance, whereas in 1886 we were approaching a period of minimum disturbance.

XV. "Seismometric Measurements of the Vibration of the New Tay Bridge during the Passing of Railway Trains." By J. A. Ewing, B.Sc., F.R.S., Professor of Engineering in University College, Dundee. Received June 20, 1888.

The absolute methods of seismometry which have been developed during recent years in Japan, and have been applied to the measurement of earthquakes there and elsewhere, may serve a useful purpose in determining the extent and manner of the shaking to which engineering structures are subject through storms of wind, moving loads, or other causes of disturbance. Existing forms of seismograph are well suited for measurements of this kind, provided the frequency

of the vibrations to be measured is neither very much greater nor very much less than is usual in earthquakes, and provided, of course, the amplitude of vibration does not exceed the capacity of the instrument. For vibrations of high frequency a greater rigidity in the multiplying and recording apparatus would be necessary; in vibrations of very long period, on the other hand, the mass whose inertia furnishes the steady-point of reference will not remain at rest. Between these extremes, however, there is a wide range within which such seismographs as are now used to measure earthquakes may be trusted to give a record that is correct in all substantial particulars, and the vibrations to be referred to below fall within this range.

The writer has recently employed his Duplex Pendulum Seismograph to examine the vibration of the new Tay Bridge while railway trains are passing over it, facilities for this examination having been kindly given by Mr. Fletcher F. S. Kelsey, resident representative of Messrs. Barlow, the engineers of the bridge. The results are perhaps worth publishing, not so much for any interest they have in themselves, as because they exemplify a novel method of inquiry which may prove of use in other cases to engineers. The duplex pendulum seismograph, which was designed for and applied to the measurement of earthquakes in Japan in 1882,* consists essentially of a pair of masses which are supported and connected in such a manner that they form an astatic combination with freedom to move in any horizontal direction. One of the two is hung from above and is stable; the other is supported from below and is unstable; and the two are constrained to move together by a ball-and-tube coupling. Their equilibrium is adjusted to be very nearly neutral, and this fits them to furnish a steady-point with respect to which motion of the ground in any azimuth may be recorded and measured. The motion is recorded by a lever, the marking point of which draws a magnified copy of the horizontal motion of the ground upon a smoked-glass plate. Fig. 1 shows the construction of the duplex pendulum seismograph as used in these experiments, and as now made by the Cambridge Scientific Instrument Company for earthquake observatories. The stable mass is a disk of lead a cased in brass (shown in section in fig. 1) hung by three parallel wires from the top of the containing box. This trifilar suspension has several advantages over the usual suspension of a pendulum from a single point; in particular it prevents twisting about a vertical axis. The unstable or inverted pendulum b is also a disk of lead below the other, and is held up by a tubular strut which ends in a hard steel point resting in an agate socket in the

* See 'Transactions of the Seismological Society of Japan,' vol. 5, p. 89, or the author's memoir on "Earthquake Measurement" ('Memoirs of the Science Department of the University of Tokio,' No. 9, 1883).

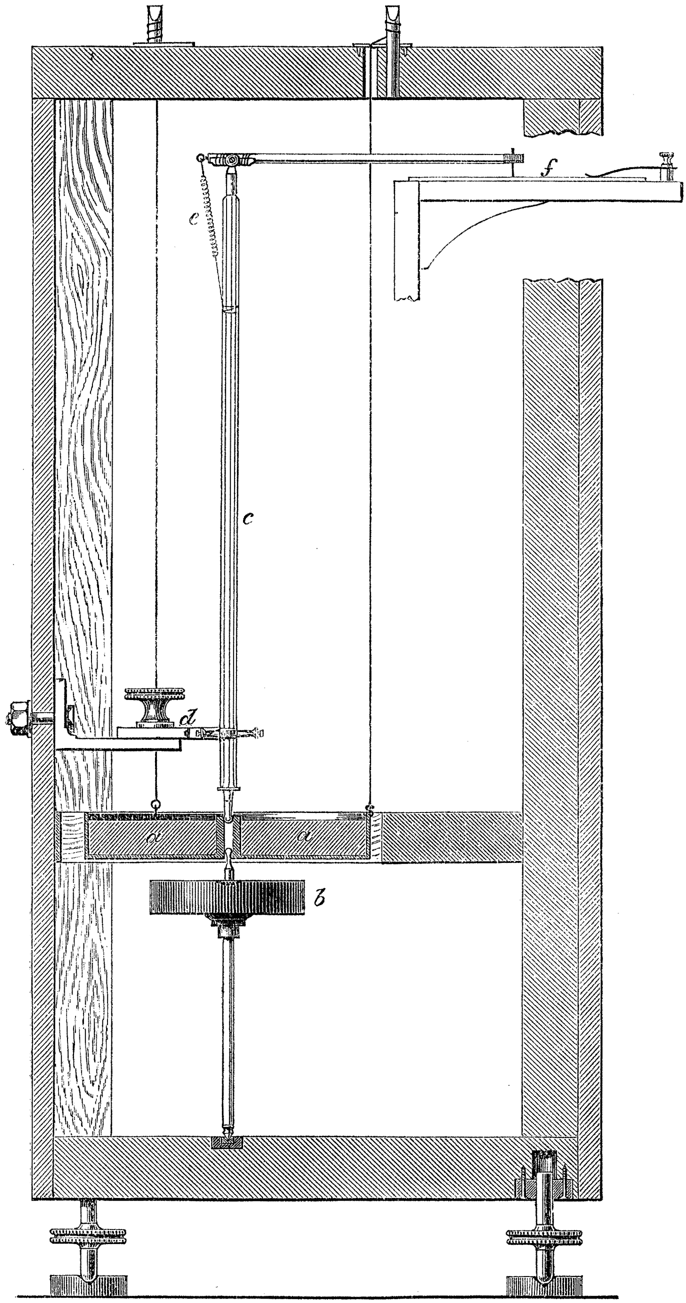

FIG. 1.—Section through Duplex Pendulum Seismograph. (Scale ¼.)

base of the box. A small brass ball attached to the lower mass *b* fits easily but without shake in a cylindrical hole in *a*, so that the two must swing together. The masses of *a* and *b* are proportioned, with respect to their distances from their respective supports, so that the equilibrium of the compound system is nearly neutral, and by way of final adjustment the upper disk *a* may be raised or lowered by turning the pins at the top until the margin of stability is as small as may be wished. The recording lever *c* is held by a gimbal joint in a bracket *d*, fixed to the side of the box, and capable of adjustment vertically and horizontally. The bottom of the lever is a ball which gears into the hole in *a*, and at the top there is a hinged index of straw with a needle-point to write the record. To reduce friction, part of the weight of the straw is borne by a spring *e*. The smoked glass plate *f* stands on a shelf which projects from one of the sides of the case, which is a triangular box. In the particular instrument employed at the Tay Bridge, the ground's motion was magnified six times.

The seismograph was set upon the ground in the six-foot way between the two pairs of rails at the middle of the length of the southernmost high girder, at a distance of about $1\frac{1}{3}$ mile from the Dundee end of the bridge, and $\frac{2}{3}$ mile from the Fife end. The girders are there 245 feet long, and stand at a height of about 110 feet above the bottom of the river and 135 feet above the foundations of the piers. Between this and the Fife shore there are 28 piers; towards Dundee there are 57 piers, and at that end the bridge forms a curve of 21 chains radius by which its direction is turned through nearly a right angle as it approaches the shore.* In this position observations were made while eight trains crossed the bridge. There was no wind, and, until a train came on, the recording index of the seismograph stood perfectly at rest.

As soon, however, as a train entered the bridge—from either end—the index began to move. The movements were at first so minute that it was difficult to estimate their range with any accuracy; allowing for the multiplication given by the lever, the movement began with longitudinal shaking through something like $\frac{1}{500}$ of an inch. In the case of trains coming from Dundee this was transmitted round the bend of the bridge and was noticed long before the train had reached the straight part. At first the movement was wholly longitudinal, and it was not until the train had come much nearer that lateral oscillation began to be felt. The interval by which longitudinal vibrations preceded transverse vibrations was much greater than could be explained by difference in their velocity of transmission. Near the

* For particulars of the dimensions of the bridge, reference should be made to Mr. Kelsey's paper in the 'Proceedings of the Institute of Mechanical Engineers,' August, 1887.

source of disturbance (as one learnt later when the train was passing the seismograph) the lateral movement was actually greater than the longitudinal; it appeared, therefore, that longitudinal disturbance reached the instrument from greater distances than lateral disturbance, because it was transmitted along the bridge with less loss. As the train came nearer, lateral movements became superposed on the longitudinal ones, and the index of the seismograph described an immense series of irregular loops, the range of which increased at first slowly and then quickly to a maximum as the train passed the instrument. Along with this progressive increase there was a periodic rise and fall in amplitude, the beat of which apparently agreed with the interval taken by the train to pass from pier to pier over successive spans. The last faint movements terminated abruptly when the train cleared the structure.

The vibrations were too numerous to allow the diagrams drawn by the seismograph to be at all clear, and a better idea of the motion was to be got by watching the index than by subsequent examination of the record. Fig. 2 reproduces two of the diagrams, and is sufficiently

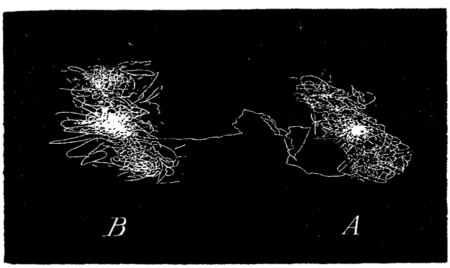

FIG. 2.—Tay Bridge vibrations, recorded by Duplex Pendulum Seismograph.

representative of the rest. As the figure is printed, the top and bottom are in the longitudinal direction of the bridge. Of the two, the figure marked A was drawn first by a passenger train coming from the south end: after it had passed the seismograph and when the oscillations were again small, it was observed that another train had entered the bridge from Dundee. The glass plate was accordingly moved by hand to a new position, and the second diagram (B) was obtained. The movements were in general of the form of nearly closed loops resembling ellipses—showing that the periods of lateral and of longitudinal vibration did not differ greatly. In the greatest movements the loops are much wider in the lateral than in the longitudinal direction. The greatest lateral movement appears to have been about one-tenth, certainly not more than one-eighth of an inch; the greatest longitudinal movement about one-fourth of this. There were about three complete vibrations per second.

The seismograph was afterwards set up just above the pier at the south end of the span in the middle of which it had previously been standing, and five more records were obtained in the new position. Except that the motion was somewhat less, they had much the same characteristics as before. The following notes refer to the passage of a slow goods-train from Dundee as observed from this position:—

Mins.	Secs.	
30	40	Train entered bridge: minute longitudinal oscillation began.
32	0	Train entered straight portion of bridge.
33	0	Lateral oscillation began.
36	0	Train passed seismograph.
38	10	Tail van of train off bridge: oscillation ceased.

In all seismometric work, whether it be the measurement of earthquakes proper, or of such shakings as these, the trustworthiness of the record depends on the degree to which the presumed "steady-point" of the instrument remains at rest during a protracted disturbance of the base. The accuracy of a seismograph admits of easy experimental test in the manner which the author described and illustrated when communicating to the Royal Society an account of his Horizontal Pendulum Seismograph, for recording separate components of motion upon a moving plate.* The test consists in placing the instrument upon a stand which may be shaken by hand, and causing a true autograph of the motion of the stand to be drawn by an independently supported index, side by side with the record that is drawn by the seismograph itself. Fig. 3 shows how this test was applied to the instrument with which the Tay Bridge observations were made. The seismograph was mounted on a stand which was constructed to give it two degrees of freedom of horizontal translation, without freedom to rotate. This was done by laying a pair of turned steel rollers parallel to each other on the top of a steady level table; a small drawing-board rested on them; on the top of it a second pair of steel rollers were laid at right angles to the pair below; a second small drawing-board lay on them, and the instrument stood upon it. The upper board was then free for translation in all azimuths, and was shaken by hand so that it imitated the motion in an actual earthquake. A record of this motion was drawn by the seismograph index, and beside it a second record was drawn by the lever and index *g* (fig. 3) which was held by a gimbal joint in a stiff bracket *h* secured to the upper board, and took its motion from a true steady-point *i* obtained by making the bottom end of the lever in the form of a small ball socketed in a

* "On a new Seismograph," 'Roy. Soc. Proc.,' vol. 31, 1881, p. 440.

cylindrical hole in the bracket *j*, which was firmly fixed to the (motionless) top of the table. When the multiplication given by this lever *g* is arranged to be the same as that given by the seismograph the two records should be identical, except for error caused by the "steady-point" of the seismograph wandering through friction, or because of the stability of the suspended mass, and except for those errors which both the seismograph and the testing lever are liable to

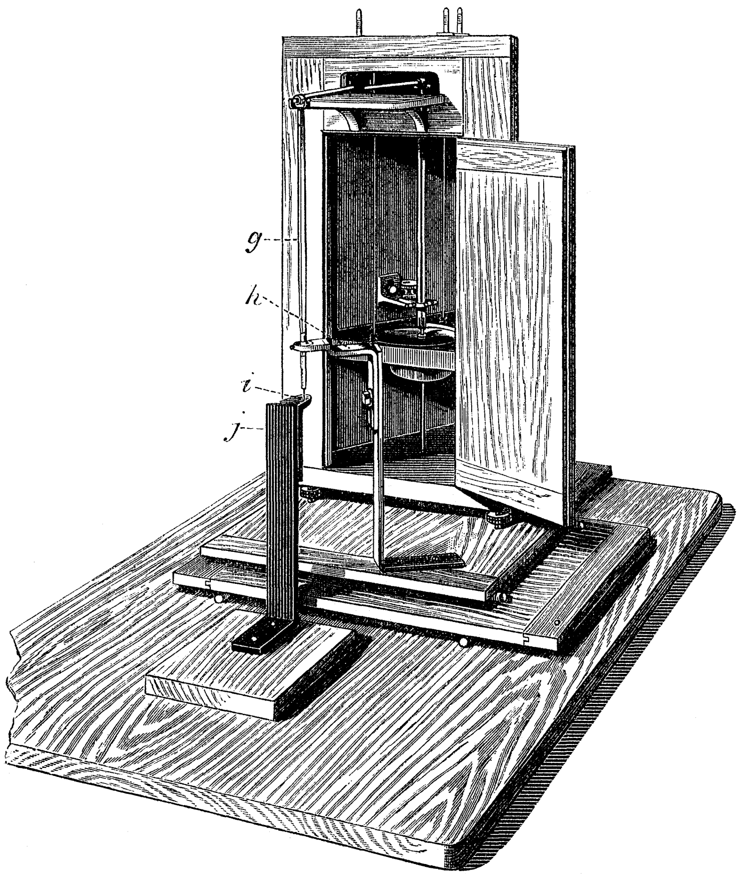

FIG. 3.—Arrangement for testing the Duplex Pendulum Seismograph.

through backlash at the joints and want of rigidity in the lever and index arm. In practice the agreement between the records is most satisfactory. Fig. 4 gives examples of the result of this test as applied to the seismograph which was used upon the Tay Bridge, when the shaking was made to imitate such movements as the

ground executes in small and in large earthquakes. Tests of this kind not only demonstrate the accuracy of the seismograph, but are a convenient means of finding experimentally the ratio in which the recording index multiplies the motion of the ground.

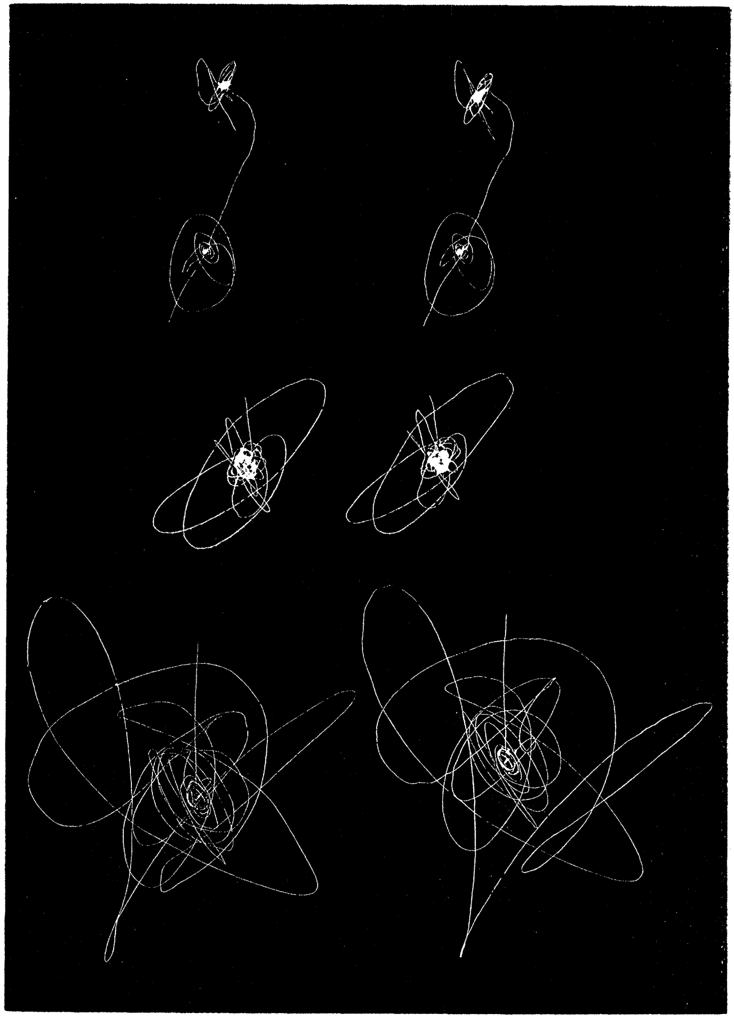

FIG. 4.—Comparison diagrams to test accuracy of Duplex Pendulum Seismograph.

For an exhaustive examination of the vibration of a structure under "live" loads, the more elaborate type of seismograph might be used, which records linear components of the motion on a surface

that is moved uniformly by clockwork. The usual form of this instrument comprises two horizontal pendulums, for the two horizontal components, and a third piece which is suspended astatically with freedom to move up and down only for the vertical component.* This arrangement employs a distinct mass and a distinct "steady-point" with respect to each component. The duplex pendulum may, however, be modified, or rather supplemented, so that it records two components of horizontal motion separately (on a moving surface) by attaching to one or other of the bobs a pair of slot guides at right angles to the direction of the two components, and pivotting in these the short ends of a pair of recording levers, so that each lever will be moved when the bob moves across the direction of the corresponding slot, but will not be moved when the bob moves along that direction. This makes a compact form of two-component horizontal seismograph, with the advantage that by retaining the ordinary index we have, in addition to the components, a plan drawn of the whole shaking. For the vertical component it is convenient to have a distinct astatically hung mass. But, as a sort of *tour de force* in astatic suspension, one or other of the bobs of the duplex pendulum may be allowed to have a limited amount of vertical freedom, and may have its equilibrium made nearly neutral for vertical displacements as well as for horizontal displacements. Let the upper bob, for instance, be hung from a platform which is free to rise and fall by rotating about a horizontal axis, and which is held up by springs. By applying the pull of the springs in such a manner that the moment of the pull about that axis is always nearly equal to the moment of the weight, we may approach vertical astaticism as closely as may be wished, and, provided the movements up and down are not too great to interfere with the proper gearing of the bobs, the mass will then possess universal freedom of translation, with nearly neutral equilibrium for all directions of displacement. In practical seismometry, however, it is no doubt advisable to restrict the freedom of the suspended mass to (at most) two degrees.

The Society adjourned over the Long Vacation to Thursday, November 15th.

* See 'Transactions of the Seismological Society of Japan,' vol. 3 (1881), p. 140, or the author's memoir on "Earthquake Measurement" cited above. A complete three-component instrument is described in 'Nature,' vol. 34, p. 343.

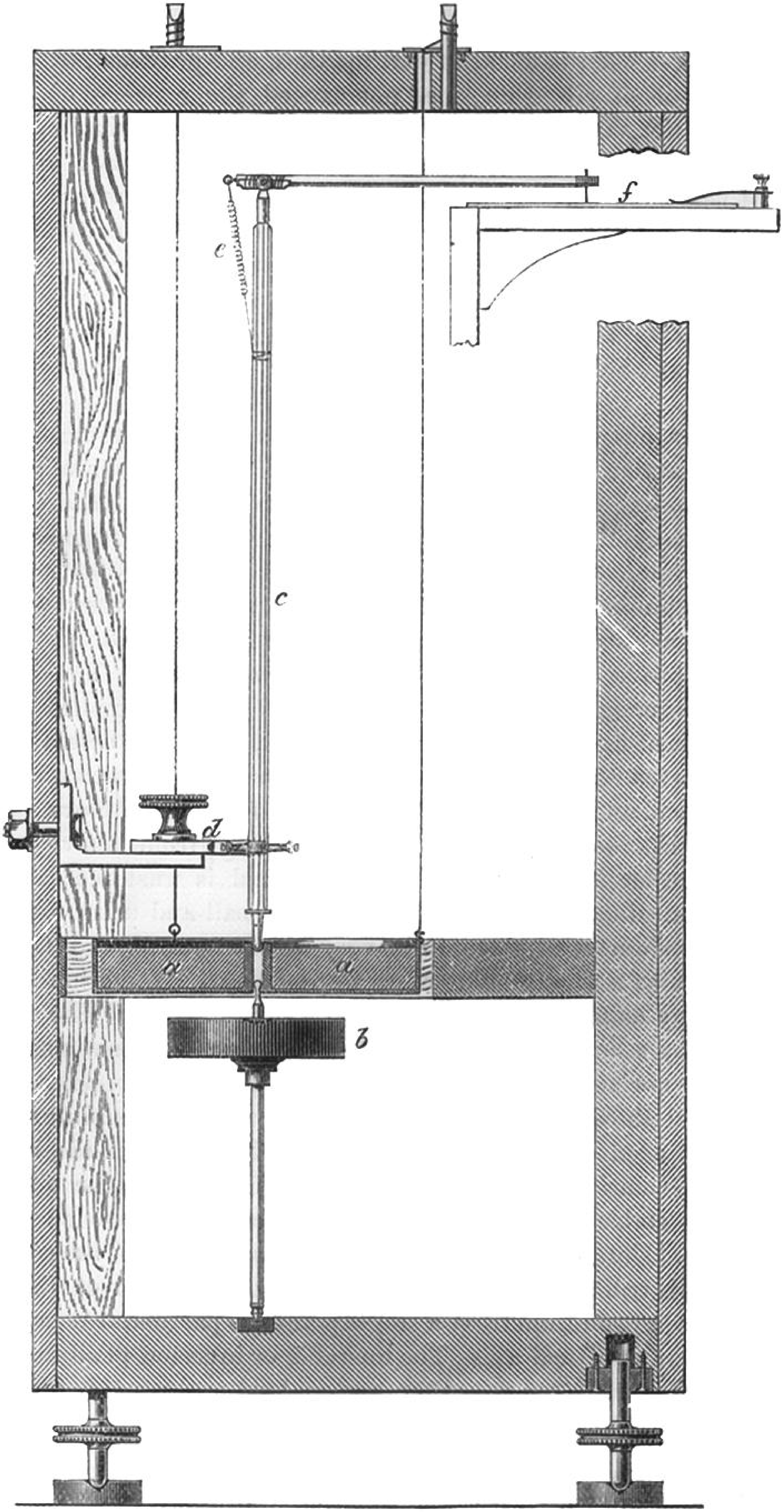

FIG. 1.—Section through Duplex Pendulum Seismograph. (Scale ¼.)

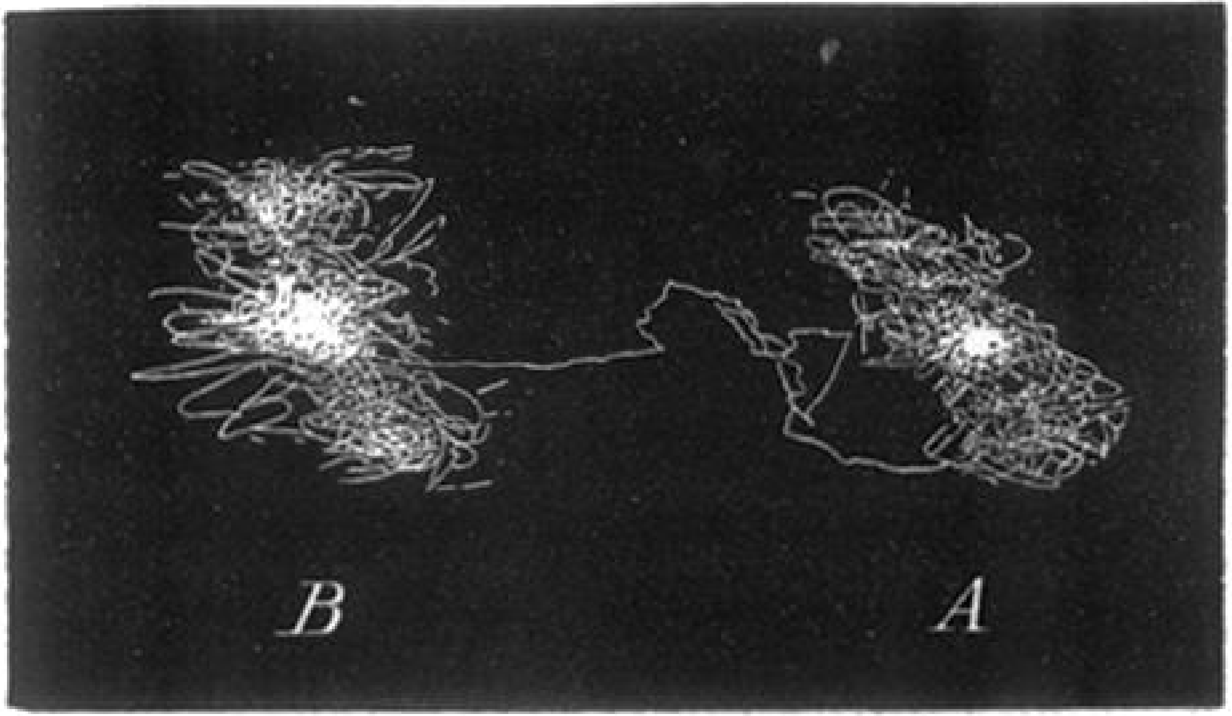

FIG. 2.—Tay Bridge vibrations, recorded by Duplex Pendulum Seismograph.

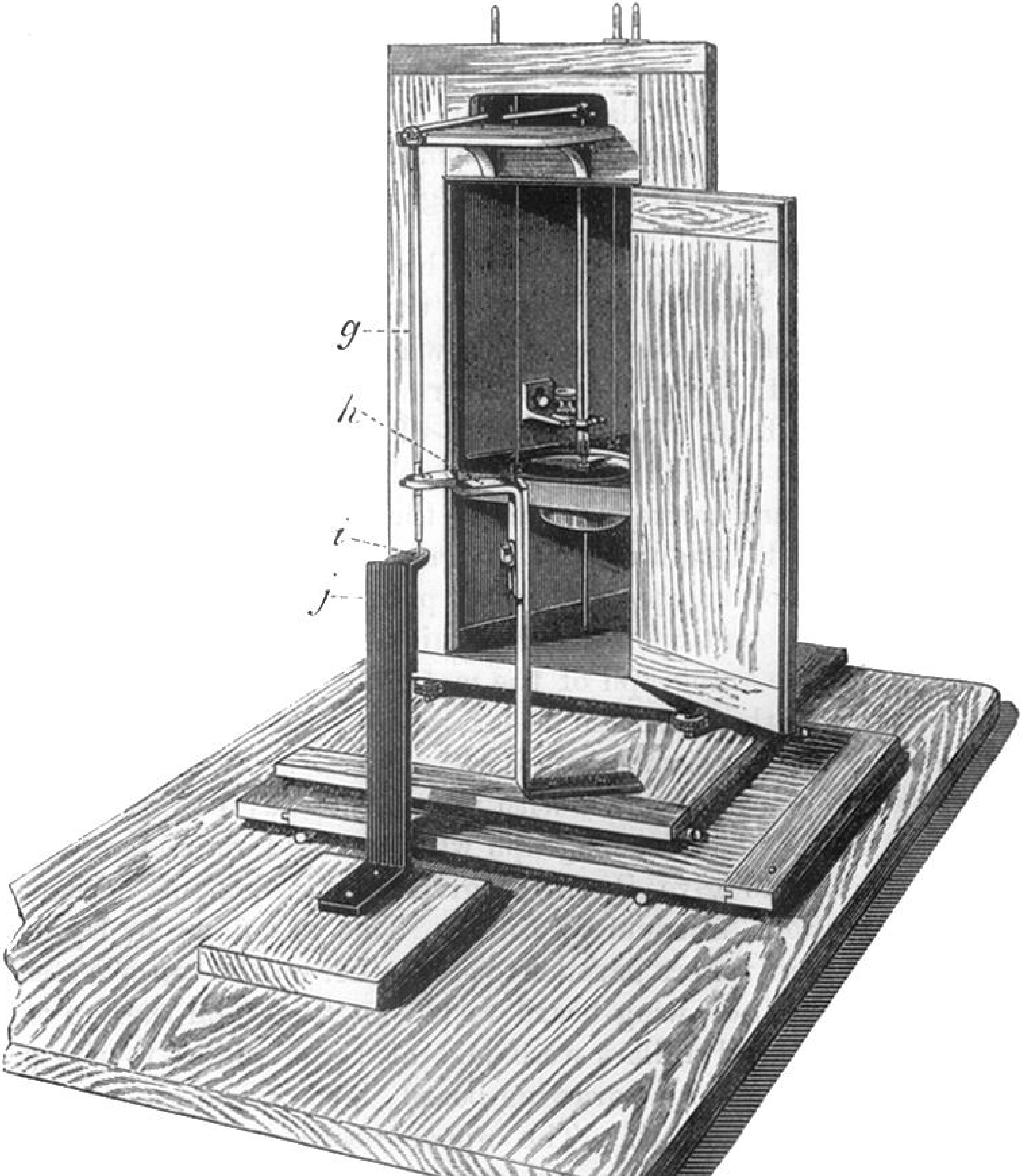

FIG. 3.—Arrangement for testing the Duplex Pendulum Seismograph.

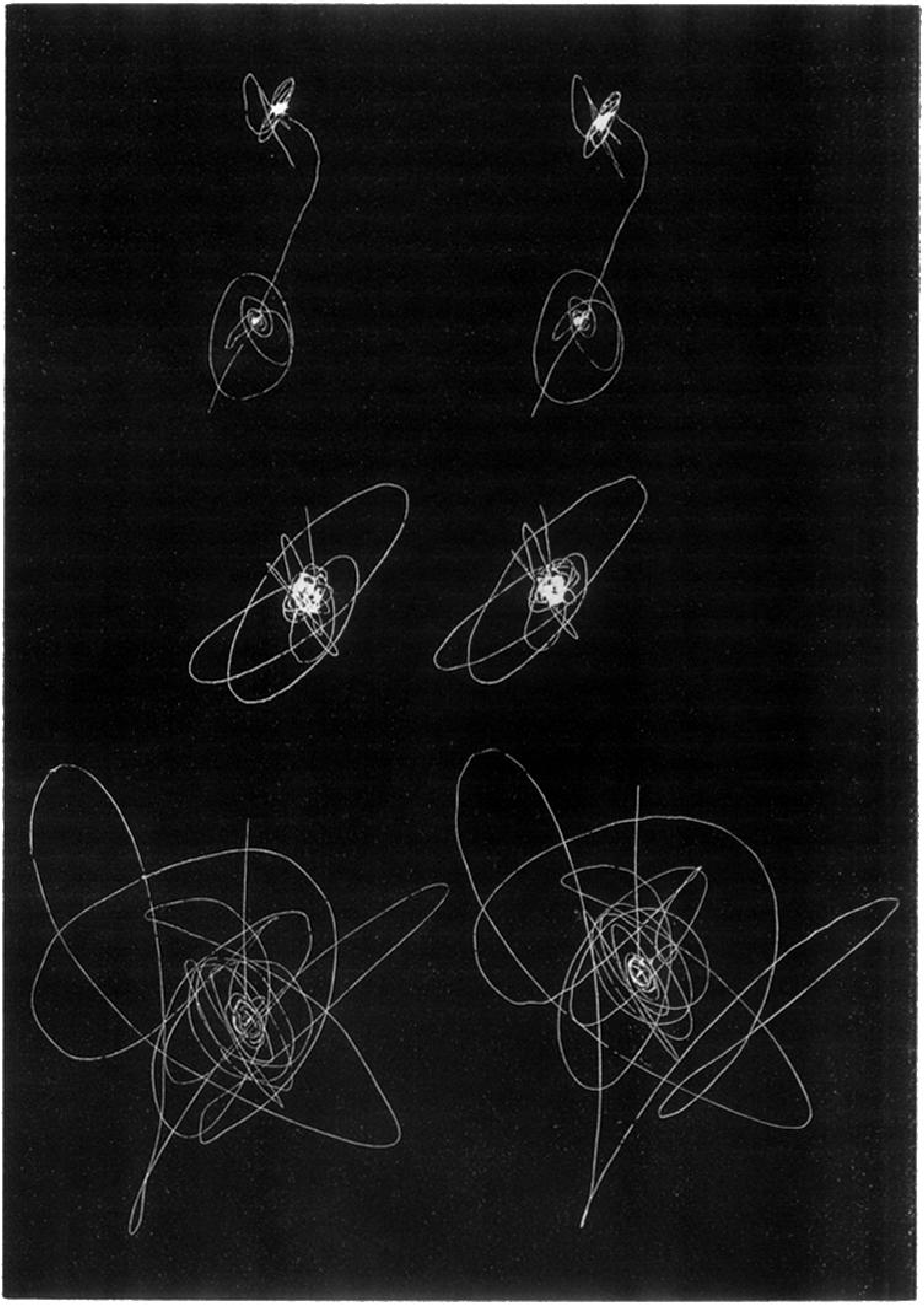

FIG. 4.—Comparison diagrams to test accuracy of Duplex Pendulum Seismograph.